Interacting single atoms with nanophotonics for chip-integrated quantum networks

Thesis by

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To my parents, sister, and loved ones.

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Abstract

Underlying matter and light are their building blocks of tiny atoms and photons. The ability to control and utilize matter-light interactions down to the elementary single atom and photon level at the nano-scale opens up exciting studies at the frontiers of science with applications in medicine, energy, and information technology. Of these, an intriguing front is the development of quantum networks where $N \gg 1$ single-atom nodes are coherently linked by single photons, forming a collective quantum entity potentially capable of performing quantum computations and simulations. Here, a promising approach is to use optical cavities within the setting of cavity quantum electrodynamics (QED). However, since its first realization in 1992 by Kimble et al., current proof-of-principle experiments have involved just one or two conventional cavities. To move beyond to $N \gg 1$ nodes, in this thesis we investigate a platform born from the marriage of cavity QED and nanophotonics, where single atoms at ~ 100 nm near the surfaces of lithographically fabricated dielectric photonic devices can strongly interact with single photons, on a chip. Particularly, we experimentally investigate three main types of devices: microtoroidal optical cavities, optical nanofibers, and nanophotonic crystal based structures. With a microtoroidal cavity, we realized a robust and efficient photon router where single photons are extracted from an incident coherent state of light and redirected to a separate output with high efficiency. We achieved strong single atom-photon coupling with atoms located ~ 100 nm near the surface of a microtoroid, which revealed important aspects in the atom dynamics and QED of these systems including atom-surface interaction effects. We present a method to achieve state-insensitive atom trapping near optical nanofibers, critical in nanophotonic systems where electromagnetic fields are tightly confined. We developed a system that fabricates high quality nanofibers with high controllability, with which we experimentally demonstrate a state-insensitive atom trap. We present initial investigations on nanophotonic crystal based structures as a platform for strong atom-photon interactions. The experimental advances and theoretical investigations carried out in this thesis provide a framework for and open the door to strong single atom-photon interactions using nanophotonics for chip-integrated quantum networks.

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